RESEARCH INVESTIGATIONS FOR NEXT-GENERATION FUSED FILAMENT FABRICATION 3D PRINTING PROCESS

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Ph.D.

In

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Introduction

Just as nobody could have predicted the impact of the printing press in 1450 or the steam engine in 1750 or the transistor in 1950 - it is impossible to foresee the long-term impact of 3D printing. But the technology is approaching, and it is likely to disrupt every field it touches. 3D printers becoming commercially viable in, but due to their price and complexity, it would be difficult to call any of them accessible or "consumer-grade." In India, the work on 3D Printing is in a very nascent stage. It is expected that the 3D Printing market in India will reach over $79 million by 2021.

3D Printers are accurate, able to create almost any intricate object, and can make products out of different types of materials. 3D printing has huge promise for manufacturing parts with improved cost and performance compared to traditional subtractive manufacturing methods. The most commonly used 3D printer is Fused Filament Fabrication (FFF). Among the various types of 3D printing, FFF has been recognized as the cheapest and the most widely adopted prototyping technology, where a thermoplastic filament is heated to melt, then extruded from the nozzle and deposited layer by layer on a support platform. (HUA17; WAN17) Another advantage of using this technology over others is the portability of the technology.

These printers have different gantry mechanisms of the print-head in 3D space. There are 3 main families of displacement, viz. cartesian, delta, and polar printer. Polar 3D printers are the simplest printers compared to the other designs as so many components are eliminated as compared to Cartesian printers. This gives a very smooth extrusion, but this technology is essentially experimental now. The comparison of these gantry mechanisms is required based on different known process parameters which can help one to establish and develop the printer in the same.

Scaling-up from prototyping operations and optimization of the process (and printed parts) across entails understanding complex and varied interactions between 3D printing machine, production process, process parameters, materials, part design, and part performance. To achieve this, significant R&D is required for researching new printer designs and printing process parameters in order to manufacture high-

performance 3D printed parts simultaneously at a low cost. This is can be better established by the computational understanding of fused filament fabrication (FFF) 3D printing process.

Experimental Test facility shall be established out of this proposed work to investigate the effect of controllable parameters of blended polymers at the melted state that controls the build process which has a dominant impact on the performance of the process, mechanical properties & surface quality of 3D printed job.

Construction 3D printing is a real challenge, but 3D printing structures at an architectural scale seem to be more and more possible. A lot of new 3D printers are arriving on the market each year, always faster and more powerful. The industry focus on large-scale 3D printers, especially for metal 3D printing. The aim is to 3D print bigger parts and realizes bigger projects. But plastic and metal are not the only materials revolutionizing the 3D printing industry. Indeed, concrete 3D printing is starting to emerge and will change the construction business in the upcoming years. Proposed research investigations will lead to innovation ready for a pilot-scale demonstration of concrete 3D printer, i.e., translation of research into technology

Several applications have been proposed in the field of medical sciences, engineering, architect, construction, household application, etc. but none has talked about the application of the same in education. Hence, we will introduce the novel applications of FFF in engineering education.

Most of the researchers talk about the positive sides of the technology but some has also pointed out the negative side of the technology out of some is the indoor air pollution by 3D printers. FFF 3D printers emit ultra-fine particles which are known but the concentration and chemical analysis need to be done which can also help the one to find the solution for the same.

In the proposed research effort will be aimed to refine, optimize and standardize the FFF based 3D printing technology. This will make India self-reliant in the field of additive manufacturing. This will mark as a step towards a new era of growth an innovation in India. The outcome of proposed will certainly provide momentum in making the technology cost-effective so that the technology sustains well in the Indian Market, which will make 3D printing technology an excellent job enabler and promote the

creation of cottage industries, start-ups, and entrepreneurs in India. The outcome shall be India can too come up with its own range of 3D printing technologies / 3D printers. To achieve this, significant R&D is required for researching new printer designs and printing process parameters in order to manufacture 3D printed parts at fast throughput simultaneously. The outcome shall be India can too come up with its own range of 3D printing technologies / 3D printers.

Review of status of Research and Development in the subject

International Status:

3D printing is considered as the future of technology in the world. Most of the world's research is done in universities and most of them are now focusing on these fields to get ahead of each other. 3D printing is a manufacturing process that will revolutionize factories and mass production in the coming years. ASTM International Committee F42 on AM has organized the span of AM processes into seven categories, differentiated largely by the means of material deposition (ALA17).

Among the variety of advanced manufacturing technologies that are currently emerging, additive manufacturing stands out as one with enormous potential for changing the distribution of manufacturing and society as a whole (HUA13). To date, investigations by researchers into the sustainability implications of AM have either been done at a broad level (GEB14; KOH15) or been highly focused on the issue of material and energy consumption (BAU11; FAL15). As a nascent research area in which the impacts of AM on sustainability are unclear. Overall "AM is expected to become a key manufacturing technology in the sustainable society of the future" (HUA13, p. 1201). Many researchers investigated the effect of FFF process parameters on the properties of the final part (RAY14) and available literature discusses improvements to the FFF process such as tool layering path (CHO10) and deposition process analysis (JIN15; WKH15). While other researchers focused on the integration of the AM process into the industrial or the education scheme (LYN16). For materials prone to distortion and warpage, the utilization of the full bed might result with parts of poor quality due to the temperature variations along the edges of the heated bed and different cooling rate, especially in an open FFF system (SUN08). Most FFF printers have its

manufacturer nozzle positioning accuracy procedure. Typical values range between 10 - 12.5 microns for the XY plane and 1 - 2.5 microns in the Z direction (ULT17; MAK17). Some equipment has even smaller values (BCN17).

The potential of 3D printing has been recognized by the US, NAMII (National Additive Manufacturing Innovation Institute) has been set up in the US to provide the innovation infrastructure needed to support new additive manufacturing products and technology in order to become a global center of excellence for additive manufacturing. In the USA industry is expected to grow at 15.7% annually between 2014 and 2019 with an approximated profit of $250.6 million and exports of $599.1 million. The research on 3D printing ranges from strengthening the existing 3D Printing systems and technology to explore new areas of printing, with new materials, and new methods of manufacturing in layers. ASME, too, has taken up AM into the system for well-structured work documentation and standardization. The biggest trend we can expect to continue to grow in 2018 is 3D printing.

Today, FFF continues to be a versatile process for rapid manufacturing of extrusion materials in applications including short-run tooling, molds, casting, end-use parts, and more. According to Wohlers Associates, publishers of the annual Wohlers Report, more than 278,000 desktop 3D printers (under $5,000) were sold worldwide last year. According to Wohlers Report 2018: “In 2017, the AM industry, consisting of all AM products and services worldwide, grew 21% to

$7.336 billion. The growth in 2017 compares to 17.4% growth in 2016 when the industry reached $6.063 billion and 25.9% growth in 2015. The total industry estimates of $7.336 billion excludes internal investments from the likes of Toyota, Adidas, Ford, Stryker, Airbus and hundreds of other companies, both large and small. A surprising number of the $1-5 billion companies – many of which are unfamiliar to most of us – are investing in AM R&D (research and development).”

The key players in this market are 3D Systems Corporation (U.S.), 3T RPD (U.K.), Arcam (Sweden), Biomedical Modeling, Inc. (U.S.), Medical Modeling, Inc. (U.S.), EOS GmbH Electro Optical Systems (Germany), FcubicAB (Sweden), Envisiontec GmbH (Germany), GPI Prototype and Manufacturing

Services, Inc. (U.S.), Greatbatch, Inc. (U.S.), LayerwiseNV (Belgium), Limacorporate SPA (Italy), MaterialiseNV (Belgium).

A recent patent application by Boeing in support of 3D printing for replacement parts revealed there are currently 20,000 printed parts on board 10 different Boeing fleets [*Boeing (2015) TCT accelerating 3D technologies—Boeing patent. In: TCT magazine + personalize., Available via DIALOG.http://www.tctmagazine.com/3D-printing-news/boeing-files-patent-for-3D-printing-aircraftparts/.*]

In April 2015, "The FAA cleared the first 3D printed part to fly on a commercial jet engine from GE." GE announced that it was working with Boeing to retrofit more than 40 GE90-94B jet engines, which power Boeing's 777 planes, with the 3D printed part—housing for the T25 sensor. [*GE Reports (2015), The FAA cleared the first 3D printed part to fly in a commercial jet engine from GE. In: GE reports., http://www.gereports.com/post/116402870270/the-faa-cleared- the-first 3D-printed-part-to-fly.*]

The sustainability studies will also help scientists, researchers and other decision-makers to understand the 3D Printing process and its implications in different applications or products. Therefore, it is extremely important to understand the influence of process variables or parameters on product development. These variables can be classified in material properties, build specifications, part positioning and orientation, and environment (MON02). Ahn et al. (AHN02) studied anisotropic behavior for different parameter combinations and analyzing the tensile and compressive strength. During this study, it was concluded that the air gap and raster orientation have more influence than other variables. The same type of study was developed by Ziemian et al. (ZIE12) in which the group evaluated the effect of raster orientation in the direction of the strain and developed the optimal levels for improving the strength of the specimen. The most studied parameters, in a static situation, have been build orientation, raster angle, raster width, raster - to - raster air gap, and nozzle diameter or slice height (BEL03; YAD18).

National Status:

When we look at the 3D printing market across the globe, India features in the top 10 countries with 7 manufacturers. US, China, and Germany top the list with 66, 42, and 22 manufacturers, respectively. The adoption of 3D printing in India is still at an early stage when compared to other parts of the world, but manufacturers across verticals are seeing the benefits of 3D printing and the value it brings. Currently, India primarily imports 3D printers from China, US, and Germany, but various government initiatives aiming to boost domestic manufacturing will result in more local 3D printing devices. With a growing focus on Make in India, a lot of Indian manufacturers placing emphasis on producing goods locally, therefore, manufacturers would need a technology which is both cost and time effective. According to the 6WResearch report, the total Indian market for 3D printing will be around $79 million by 2021, states that fused filament fabrication (FFF) based 3D printers dominate the Indian market.

NitiAyog, Government of India has put 3D Printing / Additive Manufacturing as one of the 15 disruptive technologies in science and technology roadmap for India. They have installed 3D printers in 500 schools in the first phase across the country and planning to take this drive to 2000 schools.

Prof. Balkrishna C Rao, IIT-M has emphasised 3D printing as potential areas for sustainable manufacturing and urged the Indian academia and industry could also focus on some of the latest disruptive technologies. [Need for Sustainability and Innovations in Indian Manufacturing, Yojna, Vol. 59, April 2015]

In 2015, Hindustan Aeronautics (HAL), the sole manufacturer of military aircraft in India, used 3D printing technology to manufacture components for its Rs. 458-crore 25-kN aircraft engine project. Dr U. Chandrasekhar, Former Scientist GTRE-DRDO, has pioneered the use of 3D printing in Defence R&D and set up the first-ever Additive Manufacturing centre at Gas Turbine Research Establishment (GTRE). GTRE has employed 3D printing to print ABS Plastic Quality Kaveri engine components for a detailed study. In his words: “FFF Cuts Time to Prototype Jet Engine from 1 Year to 6 Weeks. With FFF we created an engineering prototype that perfectly reflected our design intent and facilitated the complex engine development”. Since 2002, Prof. K. P. Karunakaran IITB is

leading the country at the forefront of 3D printing/additive manufacturing. He has established a dedicated state of the art Rapid Prototyping Centre at IITB. Prof. J. Ramkumar, IITK, Prof. PVM Rao, IIT-D, Prof. C S Kumar, IIT-KGP, Prof. PM Pandey, IIT-D, Prof. BB Ahuja, COE Pune, have established 3D printing centres at respective IITs and has taken number of initiatives aimed at deeply promoting and supporting progress of 3D printing research and development in country. Prof. B. Ravi, IIT-B is pioneering work in rapid tooling and rapid prototyping. Prof. S S Pande, IIT-B is developing optimal strategies for AM, Prof. Bikramjit Basu, IISc working on 3D printing of porous scaffolds. All these professors are responsible for a number of initiatives aimed at promoting and supporting 3D printing research and development in India.

Central Manufacturing Technology Institute (CMTI), Bangalore has established facilities for Rapid Product Development (RPD) currently headed by Dr C.K Srinivasa. It offers a total solution for rapid product development and consultancy. College of Engineering, Pune (COEP) in association with Central Manufacturing Technology Institute (CMTI), Bangalore are launching a one-year post-graduate diploma course in "Additive Manufacturing". CMTI has also started M.Tech programme in Additive Manufacturing at NIT Warangal.

In India, work on 3D Printing is mostly limited in the study or application end of the technology. Others are engaged in the testing with material deposition planning. In the corporate world, there are many companies that provide prototyping solutions using a variety of 3D Printer. Wipro Infrastructure Engineering where a combination of additive & subtractive technologies is used to produce functional components that use innovative designs. But due to the high cost of industrial-grade 3D Printers, there are only a few corporates that dominate the market. Being successful in experimenting with this technology, it seems that enterprises now understand the hidden potential of 3D printing.

The research in India tangents to just the study of the process and its application. Had these printers have been available at affordable prices, more and more prototyping centre would have sprung up in the market, breaking the monopoly of a few. Not much is aligned to the development of new processes and with new materials, while making the process and technology affordable and suitable in the Indian market so that India could make the best use of this technology.

Some researchers have also analyzed the effect of 3D printing in Engineering education which is suitable for classrooms and public spaces and encourages action-based learning, exploration, and innovation, to accelerate the acceptance and involvement of 3D printing technologies in the manufacturing sector (SHA18; PUS18).

Importance of the proposed work in the context of current status

The 3D printing industry has tremendous potential to revolutionize the market in India, with a possibility of creating several jobs for part-suppliers and other ancillaries in addition to the assembly companies. The current availability of 3D printers in India is through a handful of companies like MakerBot and Stratasys, which are too expensive to purchase. So, there is a need to make indigenous 3D printers with high-speed printing, best quality, and yet lower cost.

This work is important because AM is rapidly gaining popularity as a manufacturing process due in part to its ability to create unique geometries with unique material compositions across an unprecedented range of length scales from single microns to multiple meters. Further adoption of AM in large-scale manufacturing operations hinges largely on improvements in throughput and so it is vital to understand the performance limits of current AM methods in order to invent the new machine and process designs. Since its conception, FFF technology has evolved in terms of scale and material capability. Despite this evolution in capability, the fundamental mechanisms used in FFF technology have evolved very little from their original designs. Filament material is still fed into a conduction liquefier using a pinch wheel extruder. The nozzle and build platform are still positioned using a series gantry system driven by stepping motors. As a result, the FFF print rate has not improved. The high throughput FFF approach has promising future applications to the extrusion AM of nano-composite polymer resins, high throughput AM of high-performance thermoplastics, and adaptation to large-scale extrusion AM systems. Eventually, this area of research should result in a robust set of rules that can fundamentally reduce the costs associated with FFF and can assist its ascent as a feasible full-scale manufacturing process.

The work is aimed to provide a concrete printer, printing techniques and a cost-effective solution to 3D Printing and provide an alternative to the foreign 3D printers that have a high cost attributed to them. Moreover, while the research carried out worldwide is to make technology for the industries, none is aiming to make the technology for the masses and small entrepreneurs who can earn quite well using this technology. This will also enable many self-employment opportunities and make people mint money using technology. This will prove to be the next revolution in the manufacturing industries with immense scope for technological and economic advancement. Establishment of Experimental Test facility out of this proposed work to investigate the effect of different controllable parameters like speed, nozzle dimensions, build orientations, layer thickness, infill designs, etc. for blended materials will be novel and first of its kind in Country. The various sub-systems will be optimized to get the best print results. The exhaustive experimental study shall be accomplished out of this proposed work.

According to the above-mentioned 3D printing principles, there are several requirements for a matrix material that could be used in FDM. First, its melt should have proper viscosity and strength so that it can be consistently extruded out of the nozzle without breakage or buckling. Once the melt-breaking happens, not only will the time-consuming processes be interrupted but also the already started printing process cannot be continued, which will cause trouble in commercial applications. Second, when the surface of one-layer touches another, the consolidation and thermal shrinkage happen simultaneously, which may lead to unfavorable distortion. Considering the filaments would shrink after extruding from the nozzle, the volume shrinkage rate of materials would determine the dimensional accuracy of printing. It has been shown that the crystallization of material is the main factor that affects molding shrinkage. (WAN17). Finally, the mechanical properties of the finished parts largely depend on the interfacial adhesion between two neighboring layers. (SUN08; LEB18)

Since the last decade, researchers have been devoted to developing new polymer materials to obtain FDM products with both good mechanical properties and high dimensional accuracy. Polylactide

(PLA), a bio-based and biodegradable aliphatic polyester, has attracted much attention and been widely used in the FDM printing. (DRU12; HAQ17) With monomers obtained from the fermentation of starch,

PLA can be completely degraded into carbon dioxide and water under natural conditions. Moreover, during printing, compared with acrylonitrile-butadiene-styrene (ABS) copolymers and polyamides, the PLA filaments can be melted at a lower temperature. However, although having a relatively high tensile strength, PLA is a typical brittle material with extremely low elongation at break (≤3%), which has limited its applications. (GUO18; TOR16) Considering most 3D printing filaments are brittle, it is necessary to develop new ductile materials for different application requirements.

Blending can combine the advantages of the two components, which is thus one of the most commonly used modification methods for polymer materials. Chieng at al. blended PBS with poly (butylene adipate-co-terephthalate) and organomodified montmorillonite to improve the strength and modulus. (CHI10) Similarly, Okamoto et al. reported that PBS/layered-silicate nanocomposites had significantly improved the modulus but with decreased tensile strength. (OKA03) In addition, Qiu et al. prepared PLA/PBS blends with the aim of improving the ductility of PLA and the results showed that the crystallinity of PLA/PBS blends increased with the addition of PBS content. The ductility of PLA can be improved but with a compromise of stiffness and strength. (QIU16) Notably, Zhang et al. found that the tensile properties of PLA/PBS blends were higher than the anticipated values and a synergistic effect was proposed to explain this phenomenon. (ZHA18)

More importantly, that pure thermoplastic (ABS, PLA, HIPS, etc.) printed parts are usually lack of mechanical strength, which has largely limited their practical application. One of the feasible methods can be adding reinforced materials such as carbon fiber into plastic materials such as PLA can form fiber-reinforced plastic composites with high strength. Carbon fiber not only offers high strength, high stiffness, and high Young's modulus but also enhances thermal conductivity. In the carbon fiber reinforced plastic composites, the carbon fiber can be used to bear the load. Meanwhile, the plastic matrix can be used to bind and protect the fiber and transfer the load to the carbon fibers. **But less work has been done on this different next-generation blended materials and therefore in this research work the candidate would like to blend carbon with PLA/ABS or even PLA/PBS, etc. to make filaments and produce high strength and ductile materials suitable for industrial applications.**

Methodology

Material extrusion is based on molten material, which is extruded through a printing head. The most popular and used material extrusion technology is fused filament fabrication. FFF technology consists of equipment, which feeds a plastic filament wire into a liquefier chamber. The chamber is heated into a temperature suitable for melting desired plastic material according to its melting point. The filament softens and melts inside the liquefier and the filament pulling rolls pushes the molten plastic through the nozzle along with the non-molten filament. The energy required in the melting process is produced by a heater connected along with a thermistor to the nozzle. The temperature should be as low as possible in the melting point area to avoid material degradation inside the chamber or even burning which could leave burn residues inside the chamber. The molten filament is deposited onto the platform or already extruded surface by layers where it cools into room temperature and bonding with the base material. The height of the extruded layer depends on the G-code generated by the slicing software while the width of the layer depends on the diameter of the extrusion nozzle. The extrusion process starts from unwinding the plastic filament material from a roll. The feeding of the wire is handled with a pinch roller system, which is in the extrusion head. Movement of the extrusion head depends on the printer type. The filament feeding equipment feeds the filament to the printing head, which contains the liquefier for melting the plastic. The head includes also a cooler, which regulates the temperature of the printing head. The extrusion head contains an input for the filament and sinks for dissipating excess heat. The heating unit melts the plastic and the extrusion is done through the nozzle. As the material solidifies after extrusion, the shrinkage caused by cooling can be minimized by using a chamber, which is heated. The platform where the material is extruded is an XY-plane table and is usually moved by roller screw system. The popularity of technology can be seen nowadays as a variety of different printers. Printers are built in a very compact shape and easy to use even for household use and the prices are starting to be at a reasonable level.

Mechanical properties of 3D printed samples are affected by, such as layer thickness, raster angle, build orientations, fill pattern, air gap and model build temperature. Layer thickness is defined as the thickness

of the layer deposited by the nozzle. Experiments will be performed with different gantry mechanism to investigate the effect on speed, infills, printing time, etc.

Samples with different blended materials will be prepared to study the influence of layer thickness and raster angles on mechanical properties of 3D-printed parts. Tensile, compressive and bending strengths will be tested.

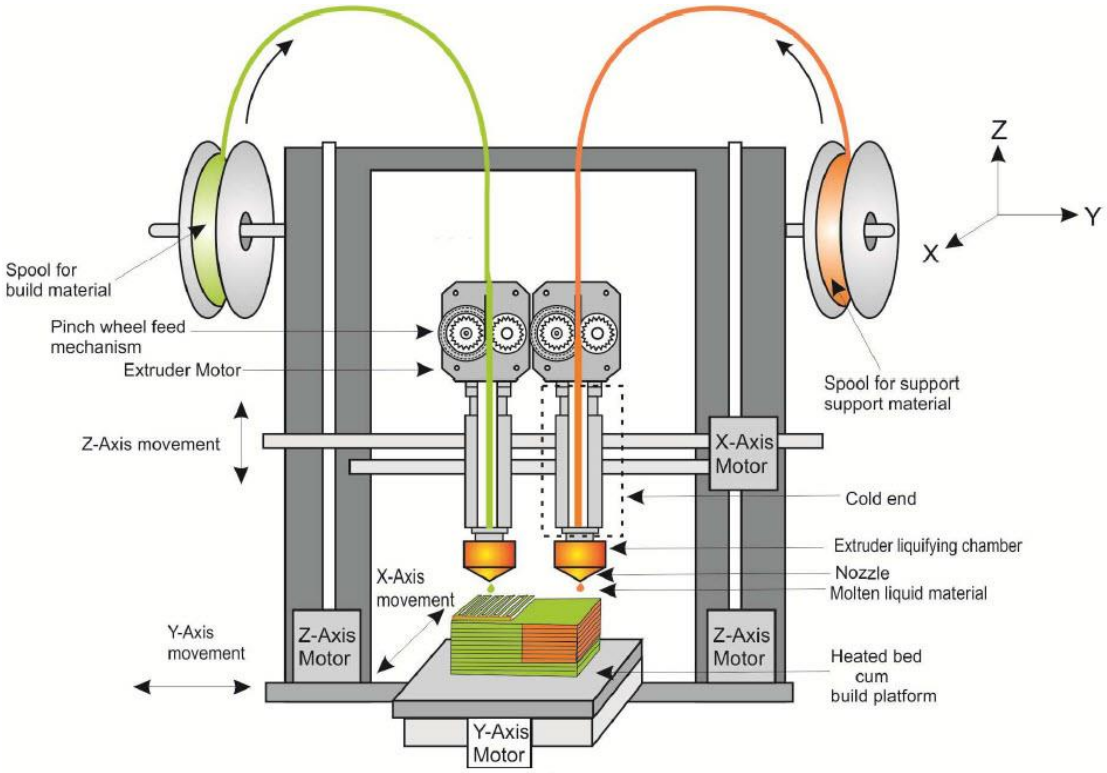

Figure: Complete FFF AM process machine setup

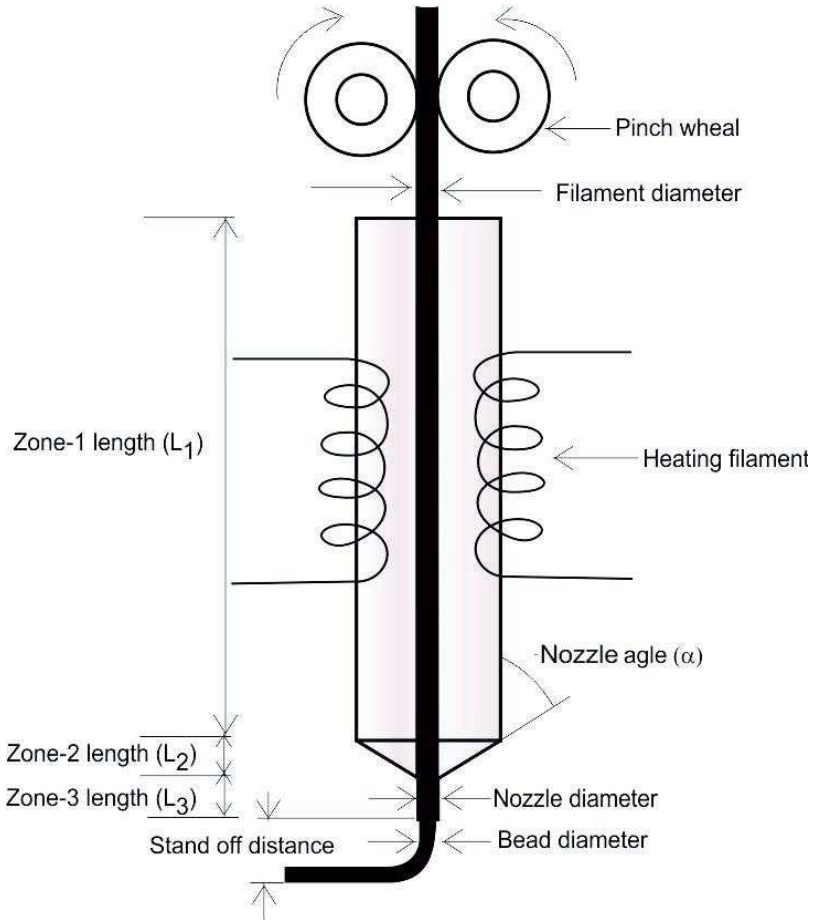

Figure: Various Zones in the extruder nozzle

Research Methodology Steps

1. Thorough literature survey of the latest advancements in the 3D printing technology.
2. Computational Study for improved understanding of FFF for the 3D Printing process.
3. Development of experimental test bench for the range of 3D Printers.
4. Experimenting with various gantry mechanism in space.
5. Experimenting with printing for different novel materials, like Carbon fiber.
6. Designing the concrete printer as light and compact as possible so as to make it viable for 3D Printing on the field.
7. Investigate the emission of ultrafine particles from 3D printers.

Research Objectives

1. Computational understanding of Fused Filament Fabrication (FFF) 3D printing process.
2. Study of various gantry mechanism in space.
3. Mechanical characterization and strength co-relationships of (blended) materials for 3D printing and study the emission of ultrafine particles during the process.
4. Pilot-scale demonstration of concrete 3D printer.
5. Novel applications of FFF in engineering education leading to innovation, incubation, and entrepreneurship.

References

GE Additive Manufacturing http://www.ge.com/stories/additive-manufacturing

[AHN02] Ahn S H, Montero M, Odell D, Roundy S, Wright PK.: Anisotropic material properties of fused deposition modeling ABS. Rapid Prototyping Journal 8, 248–257 (2002).

[ALH15] Alhart T, "GE's digital marketplace to revolutionize manufacturing", In: GE Global Research., Available via DIALOG. *http://www.geglobalresearch.com/news/press-releases/ges-digital-marketplace-to-revolutionize-manufacturing*, 2015.

[AME14] America Makes, "Fundamentals of Additive Manufacturing Materials & Processes", [Online]. Available: *https://americamakes.us/news-events/events/event/12-fundamentals-of-additive-manufacturing-materials-processes*, 2014.

[AMR16] Amar Phatak, Pande S.S, "Optimum Strategies for hollowing and part orientation in additive manufacturing", International Journal of Precision Technology, v6, Issue 1, pp 61-77, 2016.

[AST13] ASTM F2792-12a: "Standard Terminology for Additive Manufacturing Technologies", ASTM International, West Conshohocken, 2013.

[BAP05] Vijay P. Bapat and K.P. Karunakaran, "Rapid Prototyping: The Dawn of Slice Age", Search, Vol 8 No. 1 pp. 341-350 [*PDF*], January 2005.

[BAS14] Pete Basiliere, "How 3-D Printing Disrupts Business and Creates New Opportunities", Gartner G00249922, April 2014.

[BEL03] Bellini A, Güçeri S.: Mechanical characterization of parts fabricated using fused deposition modeling. Journal of Rapid Prototyping 9, 252– 264 (2003).

[BIC10] BICKEL, B., BÄCHER, M., OTADUY, M. A., LEE, H. R., PFISTER,H., GROSS, M., AND MATUSIK, W., "Design and fabrication of materials with desired deformation behavior", ACM Trans. Graph. 29, 4 (July), 63:1–63:10, 2010.

[BIG14] J. Biggs, "MIT Students Create An Ice Cream Printer", Available: *http://techcrunch.com/2014/07/16/mit-students-create-an-ice-cream-printer*, 2014.

[BRA10] Brajlih, T., Valentan, B., Balic, J., &Drstvensek, I., "Speed and accuracy evaluation of additive manufacturing machines", Rapid Prototyping Journal, 17(1), 64-75, 2010.

[BUL15] G. Bull, H. Haj-Hariri, R. Atkins, and P. Moran, "An Educational Framework for Digital

Manufacturing in Schools", 3D Print. Addit. Manuf., vol. 2, no. 2, pp. 42–49, 2015.

[CAM13] CAMPBELL, T. A., AND IVANOVA, O. S., "3D printing of multifunctional nanocomposites", Nano Today 8, 2, 119 – 120, 2013.

[CHE13] CHEN, D., LEVIN, D.I. W., DIDYK, P., SITTHI-AMORN, P., AND MATUSIK, W., "Spec2Fab: A reducer-tuner model for translating specifications to 3D prints", ACM Trans. Graph. 32, 4, 135:1–135:10, 2013.

[CHI10] Chieng, B. W. Effect of Organo-modified Montmorillonite on Poly(butylene succinate)/poly(butylene adipate-co-terephthalate) Nanocomposites. Express Polym. Lett. 2010, 4, 404– 414, DOI: 10.3144/expresspolymlett.2010.51

[DEL15] DeloitteUniversity, "3D opportunity: The course on additive manufacturing for business leaders", [Online]. Available: *http://www2.deloitte.com/global/en/pages/about-deloitte/articles/3D-printing-mooc.html*, 2015.

[DIM13] DIMAS, L. S., BRATZEL, G. H., EYLON, I., AND BUEHLER, M. J., "Tough composites inspired by mineralized natural materials: Computation, 3D printing, and testing.", Advanced Functional Materials 23, 36, 4629–4638, 2013.

[DRU12] Drummer, D.; Cifuentes-Cuellar, S.; Rietzel, D. Suitability of PLA/TCP for Fused Deposition Modeling. Rapid Prototyping J. 2012, 18, 500– 507, DOI: 10.1108/13552541211272045

[ECO12] "Print me a phone," *The Economist* (US), July 28, *http://www.economist.com/node/21559593*, 2012.

[FOR15] Formlabs, "Form 1 + High-Resolution Desktop 3D Printer", [Online]. Available: *http://formlabs.com/products/form-1-plus/*, 2015.

[GAL09] Galantucci, L.M., Lavecchia, F., Percoco, G., "Experimental study aiming to enhance the surface finish of fused deposition modeled parts", CIRP Annals - Manufacturing Technology, 49(2), pp. 189-192, 2009.

[GRA15] Granta, "Granta Design announces new solution for Additive Manufacturing data", Granta Material Intelligence. *https://www.grantadesign.com/news/2015/Additive.shtml*, 2015.

[GUO18] Guo, R.; Ren, Z.; Bi, H.; Song, Y.; Xu, M. Effect of Toughening Agents on the Properties of Poplar Wood Flour/poly (lactic acid) Composites Fabricated with Fused Deposition Modeling.

Eur. Polym. J. 2018, 107, 34– 45, DOI: 10.1016/j.eurpolymj.2018.07.035

[HAQ17] Haq, R. H. A.; Rahman, M. N. A.; Ariffin, A. M. T.; Hassan, M. F.; Yunos, M.Z.; Adzila, S. Characterization and Mechanical Analysis of PCL/PLA Composites for FDM Feedstock Filament. IOP Conf. Ser.: Mater. Sci. Eng. 2017, 226, 012038 DOI: 10.1088/1757-899X/226/1/012038

[HEA14] Brian Heater, "The CubeJet promises pro-level 3D printing in a consumer form factor for under $5,000", Engadget, January 7, *http://www.engadget.com/2014/01/07/cubejet/*, 2014.

[HOR14] Horvath, J., "Mastering 3D printing". New York, NY: Springer Science + Business Media, LLC, 2014,

[HUA13] Huang, S. H.; Liu, P.; Mokasdar, A.; Hou, L. Additive Manufacturing and its Societal Impact: A literature Review. Int. J. Adv. Manuf. Technol. 2013, 67, 1191– 1203, DOI: 10.1007/s00170-012-4558-5

[KAR04] K.P. Karunakaran, Sreenathbabu Akula and Vishal Pushpa, "Hybrid Layered Manufacturing: Direct Rapid Metal Tool-Making Process", I MECH E Journal of Engineering Manufacture, Vol. 218, No. B12, pp. 1657-1665, December 2004.

[KAT13] Katt RJ, "Materials manufacturing capabilities for sustaining defense systems", National Academy of Sciences Press, Washington DC, ISBN: 978-0-309-26757-1, 2013.

[KEL11] "3D Printing: The New Industrial Revolution", Kelley School of Business – Indiana University, 2011.

[KEL15] Kellner T, "Personalized production: the Brilliant Factory will match the right parts with the right tools", In: GE Reports., Available via DIALOG. *http://www.gereports.com/post/114774680705/personalized-production-the-brilliant-factory/*, 2015.

[KUM16] Alok Kumar, Sourav Mandal, Srimanta Barui, Ramakrishna Vasireddi, Uwe Gbureck, Michael Gelinsky, Bikramjit Basu, "Low temperature additive manufacturing of three dimensional scaffolds for bone-tissue engineering applications", Materials Science and Engineering, R: Reports Volume 103, Pages 1–39, May 2016

[LEB18] Lebedev, S. M.; Gefle, O. S.; Amitov, E. T.; Zhuravlev, D. V.; Berchuk, D. Y.; Mikutskiy, E. A.

Mechanical Properties of PLA-based Composites for Fused Deposition Modeling Technology. Int. J. Adv. Manuf. Technol. 2018, 97, 511– 518, DOI: 10.1007/s00170-018-1953-6

[MAS04] Massod S H, Song W Q, "Development of new metal/polymer for rapid tooling using FDM", Materials & Design Vol 25, No 7, p.587-594. ISSN 0261-3069, 2004.

[MAT14] Materials Today, "US$450,000 grant to develop better 3D printing simulation", In: Materials today. *http://www.materialstoday.com/additive-manufacturing/news/us450000-grant-to-develop-better-3d-printing/*, 2014.

[MIT15] MIT Professional Education, "Additive Manufacturing: From 3D Printing to the Factory Floor," Available: *http://web.mit.edu/professional/short-programs/courses/additive_manufacturing.html*, 2015.

[MON02] Montero M, Roundy S, Odell D, Ahn S H, Wright P.K.: Material characterization of fused deposition modeling (FDM) ABS by designed experiments. In Proceedings of Rapid Prototyping and Manufacturing Conference, pp.1–21. SME, Cincinnati, Ohio, (2001).

[MYE15] "The Impact of 3D Printing on the World Container Transport", M. Ye, Delft University of Technology, 2015.

[NAM15] "NAMII." [Online]. Available: *http://www.manufacturing.gov/nnmi_pilot_institute.html*.

[NIS14] "Costs and Cost Effectiveness of Additive Manufacturing: A Literature Review and Discussion", National Institute of Standards & Technology (NIST Special Publication 1176), *http://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1176.pdf*, December 2014.

[NOT15] The University of Nottingham, "EPSRC Centre for Doctoral Training in Additive Manufacturing," Available: *http://www.nottingham.ac.uk/additivemanufacturing/index.aspx*, 2015.

[OAK14] Oak Ridge National Laboratory, "ORNL, CINCINNATI partner to develop commercial large-scale additive manufacturing system," news release, February 17, *http://www.ornl.gov/ornl/news/news-releases/2014/ornl-cincinnati-partner-to-develop-commercial-large-scale-additive-manufacturing-system--.*, 2014

[OKA03] Okamoto, K.; Ray, S. S.; Okamoto, M. New Poly(butylene succinate)/layered Silicate Nanocomposites. II. Effect of Organically Modified Layered Silicates on Structure, Properties,

Melt Rheology, and Biodegradability. J. Polym. Sci., Part B: Polym. Phys. 2003, 41, 3160– 3172, DOI: 10.1002/polb.10708

[OXM11] OXMAN, N., "Variable property rapid prototyping", Journal of Virtual and Physical Prototyping (VPP) 6, 1, 3–31., 2011.

[PAN03] Pandey, P. M.; Reddy, N. V.; Dhande, S. G., "Real time adaptive slicing for fused deposition modeling", International Journal of Machine Tools and Manufacture, 43, 1 pp. 61–71, 2003.

[PEN14] Peng, A., Xiao, X., &Yue, R., "Process parameter optimization for fused deposition modeling using response surface methodology combined with fuzzy inference system", International Journal of Advanced Manufacturing Technology, 73, 87-100, 2014.

[POP15] Popular Mechanics, "MIT Creates a 3D Printer for Glass", Available: *http://www.popularmechanics.com/technology/a17012/mit-creates-a-3D-printer-for-glass/*, 2015.

[PUS18] Pushpendra Yadav, Ishant Singhal, Ankit Sahai, and Rahul Swarup Sharma.: Intensifying Hands-on Learning and Experimentation of fused deposition modelling three dimensional Printers In:7th international and 28thAIMTDR conference, Anna University, Chennai, India (2018).

[PWC14] PWC, "3D printing and the new shape of industrial manufacturing.", PWC. June 2014., p 19, Available via DIALOG. *http://www.pwc.com/us/en/industrial-products/assets/3d-printing-next_manufacturing-pwc.pdf*, 2014.

[QIU16] Qiu, T. Y.; Song, M.; Zhao, L. G. Testing, Characterization and Modelling of Mechanical Behaviour of Poly (lactic-acid) and Poly (butylene succinate) Blends. Mech. Adv. Mater. Mod. Process 2016, 2, 1– 11, DOI: 10.1186/s40759-016-0014-9

[RAY14] Rayegani, F., &Onwubolu, G. C.: "Fused deposition modelling (FDM) process parameter prediction and optimization using group method for data handling (GMDH) and differential evolution (DE)", The International Journal of Advanced manufacturing Technology, 2014.

[SHA18] Sharma Rahul Swarup, SinghalIshant, Gupta Shivam.: Innovative Training Framework for Additive Manufacturing Ecosystem to Accelerate Adoption of Three-Dimensional Printing Technologies, 3D Printing & Additive Manufacturing, 5(2), (2018).

[SIM10] T. Simonite, "I, Replicator: Self-replicating machines come of age", New Scientist, vol. 206, no. 2762, pp. 40-43, 29-May-2010.

[SIN13] Singh, R., "Process capability analysis of fused deposition modeling for plastic components", Rapid Prototyping Journal, 20(1), 69-76, 2013.

[SOO09] Sood, A. K., Ohdar, R. K., Mahapatra, S. S.: "Improving dimensional accuracy of Fused Deposition Modelling processed part using grey Taguchi method", Materials & Design, 30(10, pp.4243–4252), 2009.

[SUN08] Sun, Q.; Rizvi, G. M.; Bellehumeur, C. T.; Gu, P. Effect of Processing Conditions on the Bonding Quality of FDM Polymer Filaments. Rapid Prototyping J. 2008, 14, 72– 80, DOI: 10.1108/13552540810862028

[TEX15] "The W . M . Keck center for 3d innovation", University of Texas El Paso, El Paso, TX, 2015.

[THR04] Thrimurthulu, K.; Pandey, P. M.; Venkata Reddy, N., "Optimum part deposition orientation in fused deposition modeling", International Journal of Machine Tools & Manufacture, 44, 6(2004), pp. 585-594.

[TOR16] Torres, J.; Cole, M.; Owji, A.; DeMastry, Z.; Gordon, A. P. An Approach for Mechanical Property Optimization of Fused Deposition Modeling with Polylactic Acid via Design of Experiments. Rapid Prototyping J. 2016, 22, 387– 404, DOI: 10.1108/RPJ-07-2014-0083

[VAS15] Ramakrishna Vasireddi , BikramjitBasu , "Conceptual design of three-dimensional scaffolds of powder-based materials for bone tissue engineering applications", Rapid Prototyping Journal, Vol. 21 Iss: 6, pp.716 – 724, 2015.

[VID13] VIDIMˇC E, K., WANG, S.-P., RAGAN-KELLEY, J. AND MATUSIK, W., "OpenFab: A programmable pipeline for multi-material fabrication", ACM Trans. Graph. 32, 4 (July), 2013.

[WAN17] Wang, X.; Jiang, M.; Zhou, Z.; Gou, J.; Hui, D. 3D Printing of Polymer Matrix Composites: A Review and Prospective. Composites, Part B 2017, 110, 442– 458, DOI: 10.1016/j.compositesb.2016.11.034

[WOH18] T. T. Wohlers and T. Caffrey, Wohlers "Report 2018: 3D Printing and AdditiveManufacturingState of the Industry Annual Worldwide Progress Report", Fort Collins, CO: Wohlers Associates, 2018.

[YAD18] Yadav Pushpendra, Kapoor Shashank, Sahai Ankit, Sharma Rahul Swarup.: Effect of build orientation and infill density on mechanical properties of 3D printed parts by Fused Deposition

Modeling. In: 34th National Convention of Mechanical Engineers & National Seminar on.Mechanical Engineering and Emerging Challenges for Manufacturing, pp.118-124, The Institution of Engineers India (ISBN: 978-81-936149-8-3),New Delhi (2018).

[ZIE12] Ziemian CW, Sharma MM, Ziemian SN.: Anisotropic mechanical properties of ABS parts fabricated by fused deposition modelling. In: Gokcek M, ed. Mechanical Engineering. New York, NY, USA: In Tech, 159–180 (2012).

[ZHA08] Zhang, Y., & Chou, K., "A parametric study of part distortions in fused deposition modeling using three-dimensional finite element analysis", Journal of Engineering Manufacture. 222, Part B, 2008.

[ZHA18] Zhang, X.; Liu, Q.; Shi, J.; Ye, H.; Zhou, Q. Distinctive Tensile Properties of the Blends of Poly(l-lactic acid) (PLLA) and Poly(butylene succinate) (PBS). J. Polym. Environ. 2018, 26, 1737– 1744, DOI: 10.1007/s10924-017-1064-8